Senior Thesis

BACKARC RIFTING AND THE FORMATION OF BACKARC BASINS ALONG THE WEST PACIFIC MARGIN

by

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1995

Submitted as partial fulfillment of

the requirements for the degree of

Bachelor of Science in Geological Sciences

at The Ohio State University,

Autumn Quarter, 1995

Approved by:

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ABSTRACT:

Backarc rifting and the marginal basins formed by this rifting at convergent plate margins are the product of a combination of two processes: 1) the splitting of the volcanic arc complex due to the extensional stresses inflicted by abrasive coupling between the edge of the forearc and the subducting oceanic plate, and 2) the upwelling of magma into this newly formed split. Although there is much debate over the source of this magma, and over many other specific details of backarc basin formation, modern scientific methods have allowed researchers to gather increasingly detailed data concerning the geophysical, petrological and structural makeup of these regions. These predominantly marine basins are typically formed adjacent to volcanic island arcs, opposite their trenches. Their geographic distribution appears to be linked to the so-called "Ring of Fire", placing them alongside the circum-Pacific island arcs, predominantly on the western margins of the Pacific Ocean.

INTRODUCTION:

Backarc spreading in marginal basins is a sea-floor phenomenon that has only recently begun to be understood in any detail. By its very nature, it appears to be partially related to another very distinct sea-floor process, mid-ocean ridge spreading. However, the fact that this process seems to be widening isolated marginal basins, apparently by creating new sea-floor material within the basin, does not mean that backarc spreading behaves in all aspects like the type of divergence that occurs along mid-ocean ridges. In fact, the sea-floor spreading that takes place within some of these marine backarc basins has little else in common with ridge-associated spreading. In this paper, one model of backarc basin formation will be examined. In addition, possible explanations for some of the features associated with backarc basins will be discussed.

DISCUSSION:

The Geometry of Ocean-Ocean Convergent Plate Margins.

To begin with, it is worth mentioning a brief description of the basic geometry of an ocean-ocean convergent margin, at which a backarc basin can be formed. Before any rifting begins, the geometry of the system can be simply described as consisting of a steeply sloping trench, the volcanic arc, the forearc and the backarc **(Fig. 1)** (Taylor, 1992). The trench is the region in which one section of oceanic crust is subducted beneath another. The volcanic arc consists of an arcuate line of active, or intermittently active volcanoes. While the distance from the volcanic arc to the trench is a function of the downgoing plate's angle of subduction (which generally ranges from 30 to 60 degrees), most arcs seem to occur from 100 km to a few hundreds of km from the trench. The forearc describes the area seaward of the volcanic arc, and the backarc is the area behind the volcanic arc, opposite the trench (Kennet, 1982). Though some volcanic effects can be seen in the forearc region, they are due mostly to the dewatering of subducting sediments, and generally lack the deeper magmatic signature of arc and backarc volcanism. In areas of this kind of volcanism, forearc seamounts, chimneys and diapirs can be found. These features are composed mostly of the mineral serpentine, which is formed as water from the subducted plate is added to the ultramafic mantle rock of the upper plate. This hydrated material is less dense than the surrounding mantle rocks, and will therefore tend to rise toward the surface of the forearc (Taylor, 1992).

The Geometry of Backarc Basins.

The rift that occurs from backarc spreading in a backarc basin is found some distance beyond the volcanic front, which is the leading edge of island-arc volcanism (**Fig. 2**). As the subducted plate moves beneath the forearc, the two are coupled to some extent, either mechanically or by suction. This coupling can act to drag the front edge of the forearc downward and seaward, subjecting the forearc side of the volcanic arc complex to extensional stresses. Since the volcanic arc complex is composed mostly of andesitic rock that is generally weaker than the surrounding basaltic oceanic crust, and since the volcanic arc complex is hotter than the surrounding rocks, these extensional stresses can cause the arc to split. As a result of this split, the forearc side of the arc is now more free to gradually migrate toward the trench, pulled by the coupling with the down-going plate. This is the origin of the rift.

One possibility is to examine the relationship between the accretionary character of the trench system and the extensional forces that act to create a backarc basin. In a setting where oceanic crust is subducted beneath an island-arc complex, some degree of brittle fracture may occur along the surface of the subducted plate, due to the stress of bending downward into the trench. If the top of the subducted plate is not lubricated or smoothed by a sufficiently thick layer of sediment, then this rough, fractured surface may couple abrasively with the overriding plate more easily. Such a lubricating layer is generally absent in a nonaccretionary trench systems that are common to ocean-ocean plate convergence.

This entire process differs markedly from the process that forms backarc basins on continents. Continental backarc basins are, in one model, believed to form from the rising of a mantle diapir behind the continental volcanic chain *after* the cessation of subduction. This would imply the absence of the extensional forces that are primary to the formation of marine backarc basins (McGeary and Plummer, 1991).

Once the backarc rift has begun to form in the ocean-ocean subduction setting, subsidence occurs along the axis of the split, roughly parallel to the trench. As it continues to subside, the rift deepens and widens by continued stretching and by collapse of the adjacent rift walls (Taylor, 1992). During this time, magma is continuing to rise to the surface from the subducted plate. This magma will continue to erupt at approximately the same distance from the trench as before, except that now the terrain around that eruption has been displaced. The magma may tend to follow pre-existing channels up into the newly formed rift, even though the mantle source of this magma is migrating seaward with the forearc **(Fig. 2)**. Sediments from these eruptions fill the new rift complex, which will soon deepen and widen enough to form a young marginal basin. In addition, some combination of deep and shallow magma can begin to intrude into the rift basin, which will cause continued spreading within the basin. The resulting feature will be an asymmetric basin (Kennet, 1982). The exact origin of these magmas is open to interpretation, and a discussion of these interpretations must involve several proposed models for this process.

One hypothesis that attempts to explain backarc rifting suggests that some marginal basins spread due to processes that resemble those at mid-ocean ridges (Weissel, 1977). In this model, discrete segments of spreading occur, separated by some manner of transform faulting. This type of spreading might be responsible for the so-called "*dual-arc*" island-arcs, as seen in such areas as on either side of the Mariana Trough **(Fig. 3)**. However, another explanation of the origin of dual-arc systems is that they represent an area of subduction that failed after formation of a volcanic arc, then started again in the opposite direction, with the new trench forming in the backarc of the previous system. This would form two parallel volcanic arcs (Kennet, 1982). In another model, the spreading is seen to be more diffuse throughout the basin (Sclater, et al. 1972), so that a distinct axis of spreading, such as that seen at a mid-ocean ridge, is absent. Models intermediate to these two have also been proposed, suggesting centralized, yet relatively indistinct basin-spreading (Karig, et al. 1978).

Evolution of Backarc Basins

Ideas for the origin of the magmatism that occurs at these rift zones are equally diverse. One of the models proposed on this subject suggests a mechanism by which some portion of the relatively cool asthenosphere from the bottom-side of the overriding oceanic plate is pulled downward, coupled to the subducted plate. Eventually, this material is transported down into the more dense, viscous material below. At this point, the low-density material forms a shallow mantle partial melt that begins to rise back to the surface, initiating a flow pattern which can bring more magmatic material into the already weakened rift **(Fig. 2)** (Toksoz and Bird, 1977). This occurrence of magma remains separate in origin and surface expression from the magma that occurs at the island arc.

The formation of a marine backarc basin can be viewed as a two-part process. The first part is the structural deformation of the overlying oceanic crust, which undergoes tensional strain, possibly due to the abrasive coupling of the leading edge of the forearc with the subducted plate. The second part of the process is related to the magmatic effects that act on the backarc region. If viewed separately, these two factors can help to build a viable model for the behavior of backarc basin formation. As illustrated in **Fig.1**, the magma that forms at the initial volcanic arc rises at a distance from the trench that is a function of the angle of subduction, among other things. For the purpose of the model illustrated in **Fig. 2**, we will consider the angle of subduction to be constant, so the point of origin for the volcanic magma will not change, relative to the location of the trench. Notice also that we will use the center of the initial volcanic arc as a spatial reference, $\mathbf{D_o}$ **(Fig. 2)**.

Structurally speaking, two factors might act to separate the forearc from the backarc in this model. The first is the fact that the trench itself is constantly migrating seaward, which acts to pull the forearc away from the relatively fixed backarc. The second factor, as we have already discussed, is the abrasive coupling of the forearc to the subducted plate. As the distance from $\mathbf{D_0}$ to the trench increases, the behavior of the magma that is rising into the volcanic arc, or into the backarc, will vary **(Fig. 2)**. Over time, this rift will migrate away from the trench, then rapidly "jump" back to the volcanic arc several times, as the upwelling of the deep mantle partial melt alternates from rising in the backarc to the volcanic arc. This can produce somewhat irregular magnetic lineations over time (Bibee, et al. 1980).

Characteristics of Backarc Basins

It is interesting to note that even though the process of backarc rifting is apparently exclusive to areas where subduction is occurring, not all areas of subduction exhibit similar patterns of rifting. There are several examples of continental arc volcanism along the Peruvian and Chilean arcs that exhibit no backarc basin formation whatsoever. Even in the western Pacific margin, the extensive backarc basin complex of the Sea of Japan shows no indication of current spreading (Kennett, 1982). It is clear that the volcanism associated with plate-subduction is not the sole requirement for the onset of backarc rifting, and for the formation of a backarc basin.

It is also interesting to note that, even though there is an observable pattern to the formation of these marginal basins in various locations, there is also a great deal of variation in the forms that can be seen in such settings. In some cases, the basin is seen as a relatively simple feature, not exhibiting many deviations from the simplified model shown in **Fig. 2**. The Kuril Basin might be an example of this simple pattern of formation. A low, flat, wide basin of depth similar to that of an ocean ridge, it is relatively unobscured by any other magmatic processes. However, in some areas, lines of volcanoes can be observed truncating the backarc basin at oblique angles to the axis of the volcanic arc with lava types similar to those of the main arc complex (Taylor, 1992). To the east of the Kuril Basin, the Aleutian Basin exhibits this kind of volcanic formation in the Bowers Ridge region **(Fig. 4)**. These might be magmatic upwellings, located at zones of stress concentration (Taylor, 1992). One might also hypothesize that these volcanic ridges are the result of the subduction of aseismic ridges which were not parallel to the subducting trench. However, in the case of Bowers Ridge, it is difficult to assume that any subducted sea-floor feature could still be expressed bathymetrically nearly 1000 km from the trench.

Another anomalous feature of marginal basins is the tendency of newly formed rift fractures, adjacent to highly active arc volcanoes, to quickly fill with the lava overflow from the volcano, as well as intrusive magma. This serves to obscure the development of the rift adjacent to such volcanoes (Taylor, 1992). This might be the case along the Sulu Archipelago, which extends from an area of active volcanism in the Philippine Islands, and between two separate basins formed from a common subduction zone, the Philippine Trench **(Fig. 5)**.

Geophysical Features of Backark Basins

Several geophysical features are intimately associated with ocean-ocean plate convergence, and more specifically with the backarc spreading found in some systems. Strong gravity anomalies are nearly always associated with this type of convergent margin, particularly a high negative anomaly (approx. -3000 mgal) found over the trench, and a high positive anomaly at the volcanic arc. The former is probably caused by an isostatic imbalance, indicating a mass deficiency in the trench. The latter is likely also due to an isostatic imbalance indicating a mass excess under the arc (Kennett, 1982). While I could find no data concerning the gravitational anomaly over backarc regions, it seems likely that the thinning of the oceanic crust at this area might produce small negative anomaly measurement in the area of rifting.

Heat flow is another aspect of the island-arc convergence complex that shows a strong signature over backarc basins. When compared with other areas of the sea-floor, marginal basins often show unusually high levels of heat flow, comparable with heat flow measurements taken at mid-ocean ridges (Wantanabe et al., 1977). While it is true that a much smaller amount of new crust is produced in backarc basins than is created at mid-ocean ridges, one must consider that these are relatively large areas of young sea-floor. High volumes of heat are constantly being supplied adjacent to and beneath the basin. This will lead to high levels of heat flow for this region.

Another consideration in understanding the formation of backarc basins is the presence of intermediate to deep focus seismic activity along the arc axis. There is some suggestion that the absence of a backarc basin is associated with high levels of seismic energy released by intermediate to deep focus earthquakes along the Benioff zone (70 - 670 km deep). In fact, it has been observed that approximately 90 percent of the total global seismic energy is released in earthquakes along subduction zones that do not possess backarc basins (Kennet, 1982).

One last geophysical consideration of the backarc setting is the general lack of clearly mappable crustal magnetic lineations, such as those that distinctly identify the symmetrical spreading that takes place at mid-ocean ridges. Although magnetic mapping has been done in some marginal basins, the relatively small size of these areas makes recognizing these large-scale paleomagnetic features more difficult than recognizing the same kinds of features over thousand of kilometers along the ocean ridges (Kennett, 1982).

CONCLUSION:

Backarc basins dominate the areas behind most of the island arcs along the so-called "Ring of Fire". Their formation, once open to broad speculation, is now unfolding in great detail before scientists who are utilizing new technology to explore and model these seafloor features. Advances in our understanding of plate tectonics have allowed scientists to better understand the formation of backarc basins and the spreading that often occurs in these basins. Conversely, much of what scientists have been able to observe about the formation of backarc basins serves to reinforce and refine the theory of plate tectonics.

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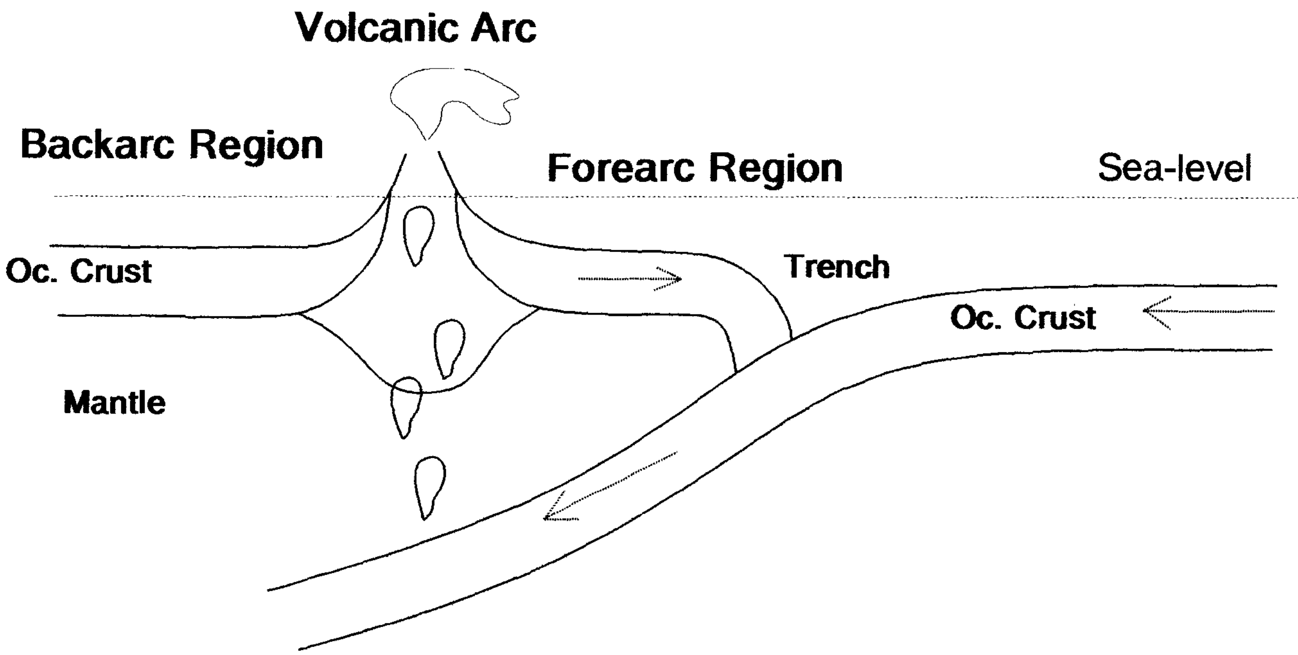
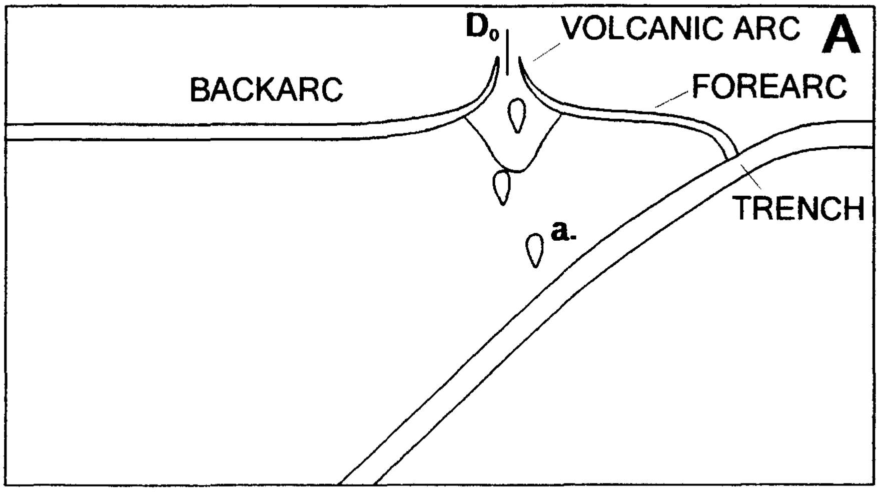


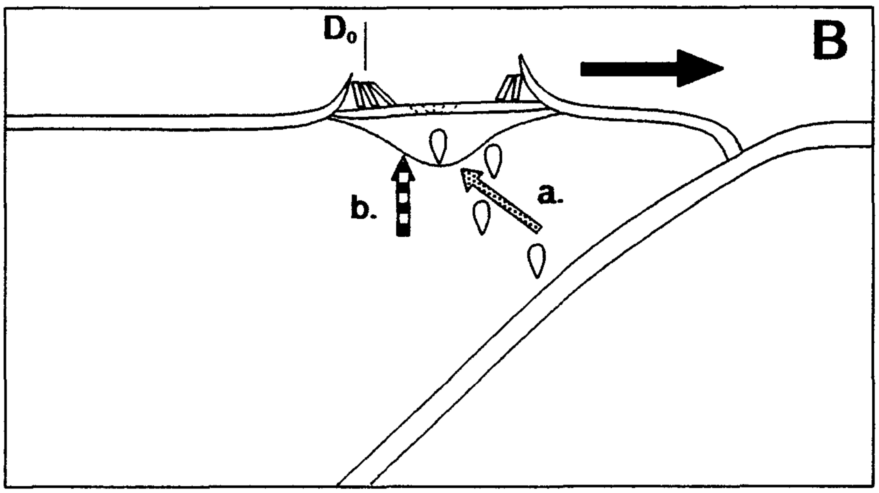
Fig. 1: As oceanic lithosphere is subducted below other oceanic lithosphere, deep mantle partial melt is produced along the subducted plate which can rise to form a volcanic island-arc from 100km to several hundred km from the trench.

Geometry of an Ocean-Ocean Convergent Margin

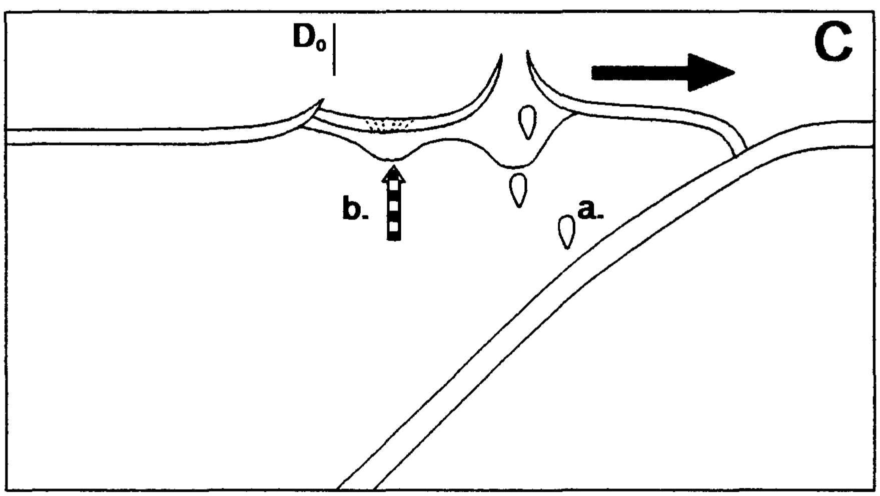
Fig. 1



Volcanic Island-Arc forms as deep mantle partial melt **a.** intrudes from the subduction of one oceanic plate under another.



Abrasive coupling of the two plates at the trench and migration of the trench seaward, leads to extensional stresses on the over-riding plate, splitting the plate near the volcanic arc. As deep mantle melt **a.** continues to rise into the newly formed basin, an upwelling of shallow mantle partial melt **b.** rises up behind the arc, intruding magma into the newly formed rift, thus continuing basin spreading.



As the forearc continues to move seaward, the point of production of the deep mantle melt **a.** moves away from the backarc basin, and this magma will again rise upward to form a new volcanic arc. The shallow mantle melt **b.** can continue to rise beneath the backarc basin, driving further rifting. This separation of melt sources, a backarc spreading center is established, behind the new volcanic arc.

Formation of Backarc Basin Rifting

Fig. 2

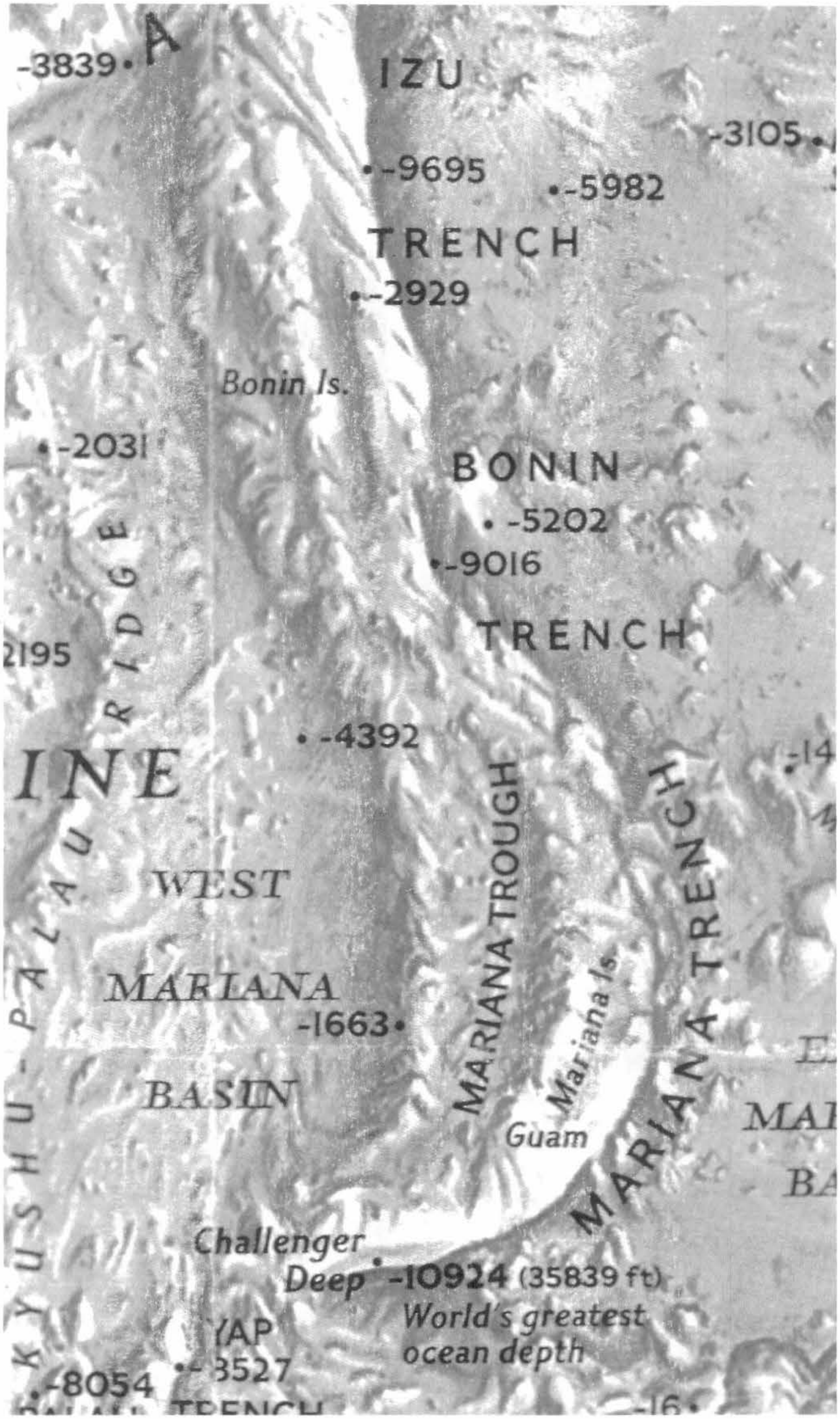


Figure 3
Bathymetric Representation of the Mariana Trench
(The National Geographic Society, 1992)

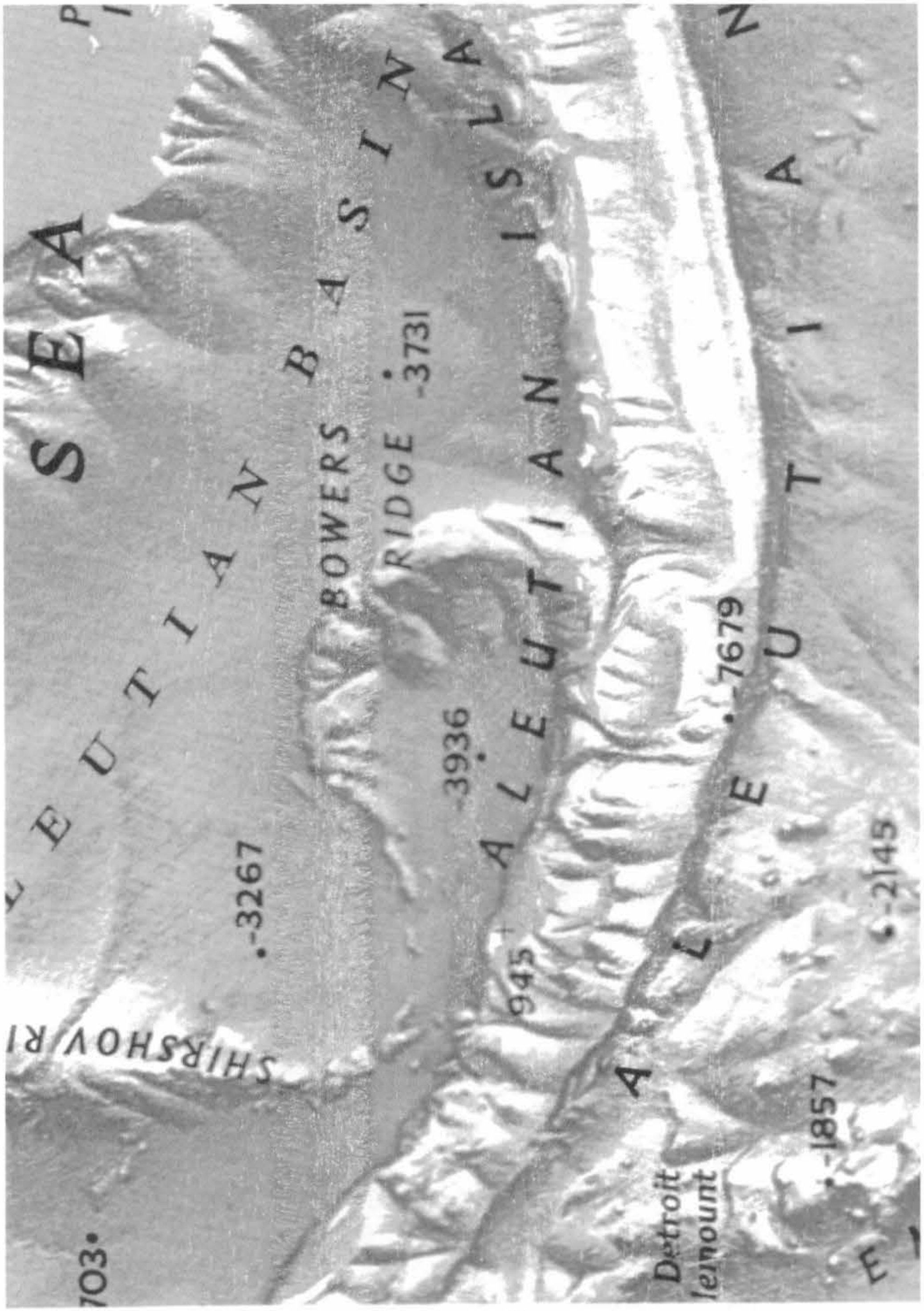


Figure 4
Bathymetric Representation of Bowers Ridge
(The National Geographic Society, 1992)

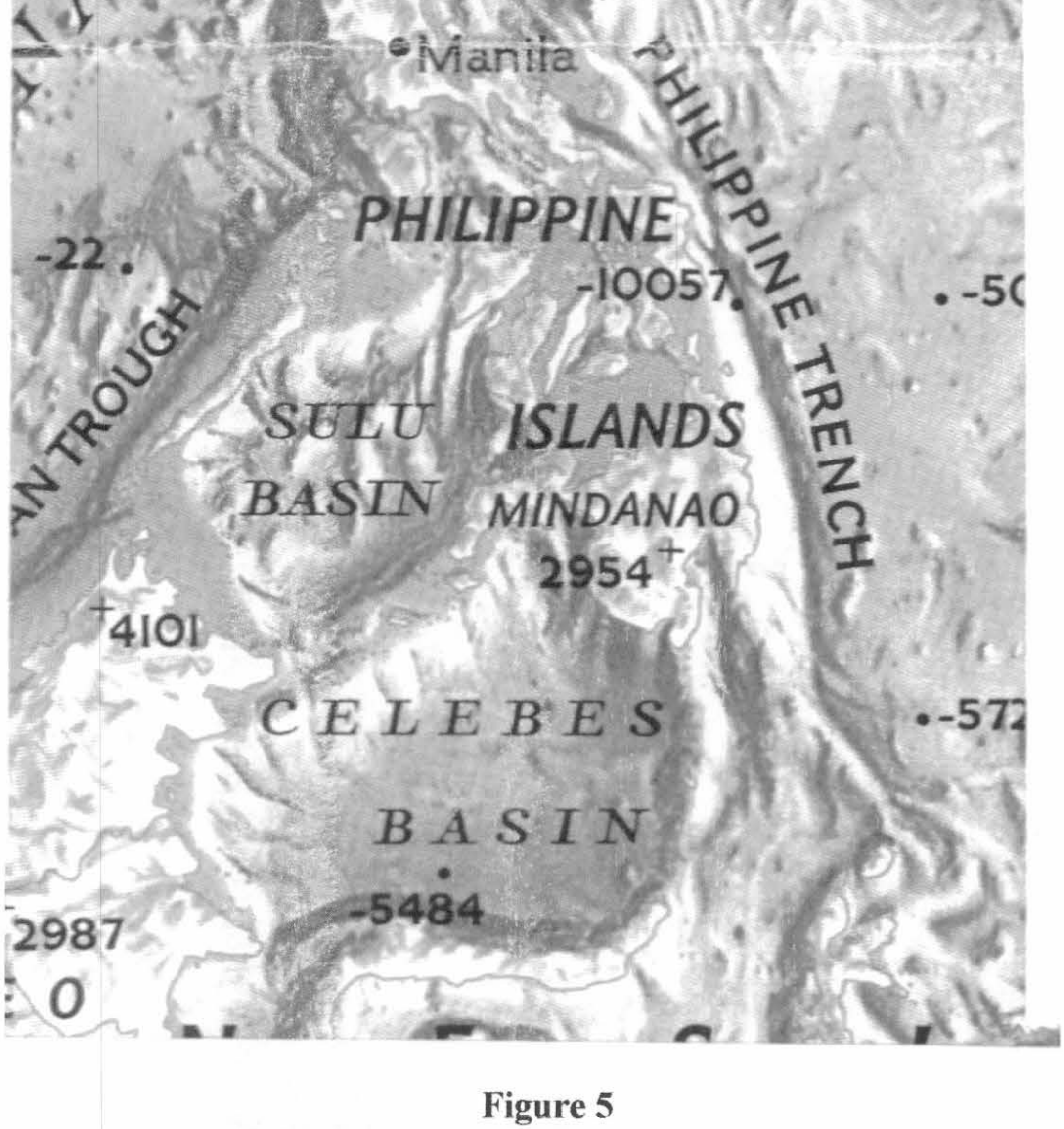


Figure 5
Bathymetric Representation of the Sulu Archipelago
(The National Geographic Society, 1992)